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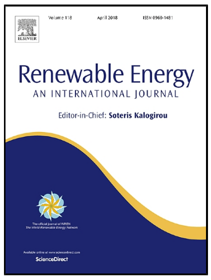

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Energy and economic losses caused by dust on residential photovoltaic (PV) systems deployed in different climate areas

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Abstract

Results of the study revealed that when dust impinged on the surface of the PV modules, monthly maximum power output of a 1.5 kWp system in Perth, Australia and a 50 Wp system in Nusa Tenggara Timur (NTT), Indonesia decreased, on average, by about 4.5% and 8%, respectively. Economic modelling showed that, the cost of production per kWh lost due to dust exhibited by these systems were A$ 0.26/kWh and A$ 0.15/kWh, respectively. Comparison of the cost of energy losses and maintenance revealed that, the Perth system would require manual cleaning in October while the system in NTT would require cleaning in August and October. Although the saving in production losses is not economically significant, this cleaning schedule was recommended, particularly for small systems in NTT since the extra output can have a significant effect on the quality of life in remote villages. The key finding was that higher dust de-rating factors and more cleaning activity may be more appropriate for PV systems deployed in tropical climate areas than that in temperate climate regions. It is recommended that PV system Standards that use the 5% performance de-rating factor due to soiling are reviewed and consideration given to climate-dependent de-rating factors.

Keywords: dust, PV performance, economic losses, maintenance cost, solar home systems

Nomenclature

A$	Australian dollar
C_M	cost of materials applied for cleaning the PV system (A$)
C_{MA}	maintenance cost activity (A$)
C_O	cost of producing or buying electricity from other sources (A$/Wh).
C_{PL}	cost of production losses (A$)
C_{WF}	cost of workforce (A$)
DCF	dust correction factor
E_L	energy losses caused by dust (Wh)
E_{PV}	daily energy produced by the PV system (Wh)
$E_{PV,c}$	energy produced by the PV system in clean condition (Wh)
$E_{PV,d}$	energy produced by the PV system in dusty condition (Wh)
f_{cable}	de-rating factor for DC cable (%)
f_{dirt}	de-rating factor for dirt/soiling (%)
f_{man}	de-rating factor for manufacturing tolerance (%)
f_{temp}	temperature de-rating factor (%)
H_{tilt}	daily solar irradiation on the tilted plane, (Wh/m^2)
L_T	load capacity over a period T e.g. monthly (Wh)
N	number of modules in the PV system
P_{max}	maximum output power of the PV module (W)

P_{mod}	derated output power of the PV system (W)
P_{STC}	rated output power of the PV module under standard test conditions (W)
$R_{selling}$	electricity selling price to the grid (A$/Wh)
$R_{purchasing}$	electricity purchasing price from the grid (A$/Wh)
T_a	the day time ambient temperature (^oC)
T_r	effective temperature rise for specific type of installation (^oC)
$T_{cell\ eff}$	average daily effective cell temperature (^oC)
T_{STC}	cell temperature at standard test conditions (^oC)
X	excess generation of the PV system (Wh)
X_{clean}	excess energy produced by the PV system in clean condition (Wh)
Y	shortfall in generation of the PV system (Wh)
Y_{dusty}	shortfall in energy produced by the PV system in dusty condition (Wh)
Υ	temperature coefficient (^oC/%)
η_{charge}	efficiency of the charge controller (%)
η_{coul}	coulombic efficiency of the battery (%)
η_{inv}	efficiency of the inverter (%)
η_{inv_sb}	efficiency of the subsystem (cables) between the inverter and the switchboard (%)
η_{pv_inv}	efficiency of the subsystem (cables) between the PV array and the inverter (%)

1. Introduction

Performance of a PV module deployed in the field declines as the amount of solar radiation decreases. One factor contributes to diminish the photon to reach solar cells is the incidence of shading (Fialho et al., 2014; Ubisse and Sebitosi, 2009). With a good design of installation, the effect of shading due to trees, buildings and other high objects can be evaded. However, the presence of dust to cover the surface of the PV module cannot be avoided. The small particles generated by natural and human activities in the environment (Calvert, 1990) scatter and absorb the incoming light (Redmond et al., 2010).

PV performance degradation from dust varies with exposure time and location. Adinoyi and Said (2013) found that dust reduces the power output of PV modules by 50% when they were exposed for approximately six months without cleaning in the eastern part of Saudi Arabia. Zorrilla-Casanova et al. (2011) noted that daily energy losses caused by dust in the south of Spain averaged around 4.4% for a year and could increase to more than 20% during dry conditions. Elminir et al. (2006), in their intensive experiments in Egypt, revealed that the energy yield of a PV module decreased about 17.4% per month for south-facing panels at a tilt angle of 45^o. Tanesab et al. (2015) reported that the degradation of power output of various PV technologies exposed to the elements for almost 18 years without any cleaning procedures in Perth, Australia ranged from 8% to 12%.

Besides the two factors mentioned previously, the effect of dust on the performance degradation of a PV module is dependent on the season. A study carried out by Kalogirou et al. (2013) in Cyprus found that the power output of PV modules reached a maximum during winter. The performance slightly decreased during spring and autumn (by a similar amount). A significant reduction was observed during the summer months. In summary, seasons with less rainfall demonstrated more accumulation of dust leading to more performance degradation. This is in line with work by El-Nashar (2003) in Abu Dhabi, UAE who reported that the highest drop of the glass covers' transmittance of a solar desalination plant was recorded during the summer season and was attributed to the increased accumulation of dust as a result of sand storms and lack of precipitation.

Performance degradation caused by dust leads to economic losses. Kaldelis and Kokala (2010) who investigated the effect of dust on PV modules in Athens found that, taking into account the potential solar irradiation in the region, 1 g/m^2 of dust could cause annual income losses as much as 400 € for a 10 kWp PV system.

Besides natural cleaning, many efforts have been performed by stake holders to mitigate the impact of dust. The actions can be classified into two approaches - restoration and prevention. The former involves manual and automatic cleaning, while the latter comprises surface modification and electrodynamic screening (Sarver et al., 2013; Sayyah et al., 2014).

A cleaning procedure should be performed when the cost of production losses *(C_{PL})* caused by dust is higher than the maintenance cost activity *(C_{MA})*, which is influenced by the cost of materials applied to clean PV modules and the cost of labour (Cristaldi et al., 2012; Faifer et al., 2014). Cristaldi et al. (2012), who investigated the economic losses of a 20 kWp system installed on the roof of a building in Milan, reported that assuming the system was cleaned in January, the next effective cleaning would be after 5 months.

In a grid connected system, C_{PL} is affected by: (1) the energy losses of the system *(E_L)*; (2) the saving value (R_S*)* i.e. the amount of income saved by electricity needs being supplied by PV modules instead of purchasing grid electricity; and (3) the incentive value *(R_{INC})* i.e. the amount of income received from excess electricity exported to the grid (Faifer et al., 2014). An expression for the cost of production losses due to dust has been formulated by Faifer et al. (2014) as $C_{PL} = E_L\ (R_{INC\,+}\,R_S)$ and applied to a case study of a 20 kW system. However, the term represents only one situation of the effect of dust on energy losses in the field and appears to overestimate the economic losses.

A comprehensive search of the literature has revealed that there are no previous studies that investigate the economic losses caused by dust on small scale residential PV systems and quantify whether its effect is significant. A simple analysis conducted by Tanesab et al. (2015) in Perth, Australia, argued that by performing manual cleaning with water, annual power losses of 12.18% due to a dust-affected module could be restored. The power could be used to supply a 5 watt light emitting diode lamp, a typical load of a solar home system (SHS), which is suitable to sustain reading activity for about 12 hours.

This study was carried out to investigate energy and economic losses caused by dust on typical residential PV systems deployed in the two different climate areas of Perth, Australia and Nusa Tenggara Timur (NTT), Indonesia and identify the cost effectiveness of cleaning as part of regular maintenance. The study aims to expand the work of Faifer et al. and develop an economic model that covers different situations of dust-affected PV output in relation to realistic load profiles.

The following research questions will be answered in this paper:

- What are the energy and economic losses caused by dust on a typical grid-connected PV system in Perth and an off-grid SHS deployed in NTT?
- Does the cost of energy production losses of the systems warrant cleaning of the modules and if so, what is the optimal schedule for cleaning?

2. PV performance degradation caused by dust

The seasonal effect of dust on the performance of PV modules in Perth and NTT had been studied in previous research by the authors. As a temperate climate area, Perth is situated at

31.95° South latitude and 115.85° East longitude. It has four seasons comprising of summer (December to February); autumn (March to May); winter (June to August); and spring (September to November). Meanwhile, NTT, which is a tropical area, exhibits two seasons, namely, the dry season (April to October) and the wet season (November to March). NTT is located in the Eastern part of Indonesia with a geographical location of 10° South latitude and 123° East longitude.

PV performance measurements in Perth were conducted from the beginning of December 2014 to the end of November 2015 on three PV modules deployed at the Renewable Outdoor Testing Area (ROTA), Murdoch University. The modules pointed to North with an inclination angle of 32° were typical of PV technologies used in the region e.g. amorphous silicon (a-Si), polycrystalline silicon (pc-Si), and mono-crystalline silicon (mc-Si). Meanwhile, performance measurements on PV modules in NTT were initiated in the beginning of November 2014 and ran to the end of October 2015. Four PV modules (two pc-Si and two mc-Si), installed at Kupang State Polytechnic (PNK - Politeknik Negeri Kupang) and facing North with an inclination angle of 10°, were chosen to represent PV modules in NTT. All PV modules were washed with clean water so that they started in a clean condition at the beginning of the study. At both sites, measurements were performed at the end of every season in order to capture a worst case soiling scenario e.g. PV modules being left all summer (or dry season) to collect dust. Weather and environmental conditions during the study period were recorded and then used to analyse the experimental results in relation to the impact of dust.

The maximum power output (P_{max}) of the PV modules deployed at ROTA and PNK was recorded using a solar module analyser. The performance results were then transposed to standard test conditions (STC), referring to solar intensity 1000 W/m^2, temperature 25 °C, and air mass 1.5, by applying procedure 1 of the IEC 60891 standard (International Electrotechnical Commission, 2009). To compare the PV modules' performance, the transposed result of each PV module was normalised by using, as a reference point, its P_{max} output value in a clean condition, measured at the initial stage of the study. The results are depicted in Fig. 1 and 2.

The figures show that initially clean PV modules produced their maximum power output, which then decreased with certain site-dependent patterns after exposure to the elements. Variation in performance degradation indicates that the amount of dust accumulated on the modules' surfaces was different over the seasons of the study period. The amount of dust that attaches to the modules was strongly influenced by weather and environmental conditions. The greatest drop in performance was noted during the seasons with less rainfall, i.e. at the end of summer in Perth and at the end of dry season in NTT. These results are supported by the climatological data in Table 1 that reveals there were only 5 rainy days at ROTA during the summer season (December - February). Three occasions of rain occurred in the second and the third day of February 2015 (Murdoch University Weather Station, 2016). The less rainfall, understandably, could not wash away all the dust from the PV surfaces. In contrast, raindrops can gather dust particles in the atmosphere as they fall and this dust can then get deposited on the PV surface, exacerbating PV performance degradation (Sarver et al., 2013). It was also recorded that there were several buildings being renovated at ROTA in the end of spring. Vehicles and worker activities can cause more accumulation of dust in the atmosphere and subsequently more dust on the surface of the PV modules. This may explain why, in Fig. 1, the P_{max} degradation of PV 1 (mc-Si) and PV 2 (pc-Si) at the end of spring was lower than that at the end of summer. PV 3 (a-Si), however, does not follow this trend and it may be that it was not affected by the activities as its location was far away from the road used to access the buildings. As a tropical climate region, NTT exhibits a longer period of dry season (April to October) than Perth. Table 1 shows there was only one rainy day in July for the last five months of the dry season in NTT. The long dry season caused more dust to build up on PV surfaces leading to its significant degradation. Improvements in performance (without cleaning) were noticeable in seasons with more rainy days such as winter and wet seasons in Perth and NTT, respectively. Table 1 shows that there were 39 rainy days in Perth during winter (June - August) and 74 in NTT during wet season (November - March). These greater rainfalls were able to clean away significant amounts of dust concentrated on PV surfaces.

Comparing the two sites, it was found that over the examined periods (one year), the performance degradation of PV modules in NTT (12-15%) was higher than that in Perth (4-6%). This indicates that the quantity of dust on PV surface in NTT was greater compared to that in Perth. There are a number of possible reasons for this; the long dry season that caused dust build-up, lower PV inclination angles that made the cleaning processes performed by rain and gravitation more difficult, and higher relative humidity that supported the cementation of dust on the PV cover glass.

3. A brief review of residential PV systems in Perth and NTT

The application of PV systems to produce electricity is growing very rapidly in Australia. The Australian Photovoltaic Institute noted that Australia has the highest proportion of residential PV systems in the world (16.5%) and the majority of PV systems are small-scale household rooftop systems with now around 5 GW of installed PV in systems less than 10 kW in rated power (Australian Photovoltaic Institute, 2016). This success has been driven by the significant reduction in cost of PV module as well as government support by providing a variety of programs to attract the community to install PV systems. One key support mechanism has been the generation of Renewable Energy Certificates (REC) as part of the Renewable Energy Target (RET). Through this scheme, the owners of small scale PV systems (0-100 kW) receive an up-front discount from retailers that reduces the total installed cost of the system. During the period 2009-2012, customers were eligible to receive up to 5 times the amount of RECs on systems that were less than 1.5 kWp in capacity (Ross et al., 2012).

In addition to REC schemes stipulated by the Federal Government, there have also been some feed-in-tariff (FiT) programs set-up by State Governments in the past seven years. Via this type of program, PV owners receive extra income by selling the excess electricity produced by their systems to the grid.

In Perth, one in every five households has a rooftop PV system and combined capacity has now reached 500 MW (PV Magazine, 2016). The systems are applied in parallel with the grid to supply the energy needs of the household and popular system sizes are 1.5; 2; 3; 4; 5 and 10 kW (Solar Choice, 2017).

For the purpose of rural electrification, PV modules are also deployed in some remote areas in NTT. Most PV systems in the region are small-scale off-grid systems commonly known as solar home system (SHS). A typical system in NTT features a 50 Wp PV module, a lead acid battery with capacity 70 Ah, a 12 Volt and 10 Amps solar charge controller, three light emitting diode/LED (6 to 10 Watts each) and one DC outlet socket for low power consuming appliances such as a television (20 W) and a radio/cassette player (6 W) (Retnanestri et al., 2003).

The government has encouraged the community to use SHSs through financial incentives such as the credit schemes applied in NTT to increase the affordability of the systems to the users. The scheme allows householders to deposit a down payment of 20% of the cost of the system and pay the rest by instalments over a period of 2 to 3 years (Pode, 2013).

4. Energy produced by a PV system

The average energy produced by a PV system per day (E_{PV}) is expressed by (Australian/New Zealand Standard, 2010; Clean Energy Council, 2013):

$$E_{PV} = P_{mod} \times H_{tilt} \times N \quad (1)$$

For a grid-connected PV system (Clean Energy Council, 2013):

$$P_{mod} = P_{STC} \times f_{man} \times f_{temp} \times f_{dirt} \times \eta_{pv\_inv} \times \eta_{inv} \times \eta_{inv\_sb} \quad (2)$$

For an off-grid PV system such as a solar home system designed to operate independently, a battery bank is required to back up electricity needs during the night or cloudy periods. Thus, P_{mod} of an off-grid system is determined by equation (Clean Energy Council, 2013):

$$P_{mod} = P_{STC} \times f_{man} \times f_{temp} \times f_{dirt} \times f_{cable} \times \eta_{coul} \times \eta_{charge} \quad (3)$$

Furthermore, correction factor of temperature f_{temp} is given as (Clean Energy Council, 2013):

$$f_{temp} = 1 + (\Upsilon \,.\, (T_{cell\ eff} - T_{STC})) \quad (4)$$

$$T_{cell\ eff} = T_a + T_r \quad (5)$$

5. Economic losses caused by dust

Cost of production losses (C_{PL}) is dependent on energy losses caused by dust, E_L (in Wh), which is the difference in energy produced by the PV system in a clean condition ($E_{PV,c}$) compared to a dusty condition ($E_{PV,d}$):

$$E_L = E_{PV,c} - E_{PV,d} \quad (6)$$

In grid-connected systems, any excess energy produced by the PV array is exported to the grid while any shortfall is met by importing electricity from the grid, where:

Excess generation, $X = E_{PV} - L_T$, and (7)

Shortfall, $Y = L_T - E_{PV}$ (8)

Three possible situations were formulated for grid-connected systems with regards to the impact of dust on the cost of production losses:

- The energy losses caused by dust reduce the amount of excess energy exported to the grid without leading to shortfall, and the cost of production losses is given by:
  $$C_{PL} = E_L \,.\, R_{selling} \quad (9)$$
- The energy losses caused by dust increase the existing shortfall, and the cost of production losses is given by:
  $$C_{PL} = E_L \,.\, R_{purchasing} \quad (10)$$
- The energy losses caused by dust decrease excess output exported to the grid, but also reduce energy for self-consumption so that electricity must be imported from the grid to make up the shortfall. In this case the cost of production losses can be shown to be:
  $$C_{PL} = E_L (R_{selling} + R_{purchasing}) - X_{clean} \,.\, R_{selling} - Y_{dusty} \,.\, R_{purchasing} \quad (11)$$

For SHSs that are off-grid systems the energy produced is commonly used for self-consumption only. The presence of dust reduces the amount of power from the system and, in the worst case scenario, increases the shortfall so that the owner has to provide electricity from other sources such as diesel or petrol generator to meet the needs of the household. Accordingly, the C_{PL} can be calculated by:

$$C_{PL} = E_L \,.\, C_O \tag{12}$$

Further, as stated in (Cristaldi et al., 2012; Faifer et al., 2014), maintenance activity cost (C_{MA}) is expressed by:

$$C_{MA} = C_M + C_{WF} \tag{13}$$

A cleaning procedure should be performed when $C_{PL} \geq C_{MA}$ (14)

6. Methodology

Simulation of the effects of dust was performed in three scenarios as explained below:

- In scenario 1, it was assumed that the PV modules were cleaned every day so that the loss caused by dust was 0%.
- In scenario 2, it was assumed that the effect of dust was a constant 5% power degradation over the study period, as per the losses recommended by AS/NZS 4509-2:2010 (Australian/New Zealand Standard, 2010).
- In scenario 3, it was assumed the effect of dust was that observed in the field at the end of every season as shown in Fig. 1 and 2, with a further assumption that the effect is linear between the consecutive seasons. For this scenario, the PV modules with the worst performance were chosen to provide an overview of the worst impact of dust on the economic losses in both areas. The modules are PV 2 (pc-Si) and PV C (pc-Si) for Perth and NTT, respectively, with a degradation pattern over the months as shown by the dashed lines in Fig. 1 and 2. To adopt the degradation pattern for the residential PV systems in Perth and NTT, the monthly P_{max} output of modules proposed for the systems was multiplied by monthly dust correction factors *(DCF)* for each region, calculated from the chosen PVs i.e. PV 2 (pc-Si) and PV C (pc-Si). The *DCF* for a certain month (see Fig. 3) is the average of daily P_{max} output over a month normalised by P_{max} reference, which is P_{max} recorded in clean conditions at the beginning of the study.

For the selected residential PV systems in both locations, energy produced by the systems was calculated by deploying the equations in section 4. PV module performance data for each of scenarios 1 to 3 were then applied to calculate the energy and economic losses using the formulas in section 5. In addition, the cost of materials and labour for cleaning the system was estimated to determine maintenance cost activities. A decision of maintenance procedures was then made by considering the economic result and cost of maintenance activities. The summary of the methodology is shown in Fig. 4.

7. Supporting data for typical small-scale PV systems in Perth and NTT

During 2009-2012, a 1.5 kWp grid-connected PV system was the most common system installed in Perth due to the terms of the Solar Credits Scheme (Ross et al., 2012). Many of these systems exist in Perth today and therefore, a 1.5 kWp system was selected for simulation in this study. The Australian Government's 'Energy Made Easy' electricity usage calculator (Energy Made Easy, 2016) was used to calculate the average household electricity usage based on a 2014 survey of 4000 households. The calculator shows the average electricity consumption in each season for a typical house in your localised zone with the same number of occupants as in your house. For this research the calculator was used to estimate the monthly average daily energy consumption for a 4-person household in the suburb of Kardinya in the Perth metropolitan area (see Fig. 5). This estimated has assumed that the average daily energy consumption does not vary significantly between months for each season.

Based on the explanation in section 3, it was assumed that a SHS in NTT contains typical loads with characteristics as shown in Table 2. It is noted that an element of customer demand management is important for a SHS. It was assumed the lights were supplied by battery during the night, and the other loads were during the day time so that the system could handle the loads without interruption.

To calculate the energy produced by the residential PV systems, all de-rating factors were sourced from (Australian/New Zealand Standard, 2010; Clean Energy Council, 2013) and are summarised in Table 3. Ten 150 Wp mc-Si PV modules, mounted parallel with the roof, were assumed for the typical 1.5 kWp system in Perth. Meanwhile, for a SHS in NTT, a 50 Wp mc-Si PV module mounted on a free standing frame on the roof was considered. As well as the selected typical PV systems and load characteristics, monthly solar irradiation and ambient temperature of the case studies areas were compiled as depicted in Table 4.

To determine the maintenance activity cost *(C_{MA})*, the workforce cost *(C_{WF})* and material cost *(C_M)* were fisrt estimated. Manual cleaning with water was assumed for the study as it is considered as the most suitable way to clean away dust from PV surface for a small scale PV system (Mohamed and Hasan, 2012). Based on the authors' experience, it takes about 5 minutes to clean one PV module. Taking into account the minimum wage in Perth is about A$ 18/hour (Department of Commerce, 2016) and estimating the cost for cleaning materials, including clean water, is A$ 8, then the total cost needed to clean the 10 PV modules by the owners in Perth is about A$ 23. By performing a similar procedure and with a similar cleaning time, the owners of the SHS in NTT would spend about A$ 0.5 to clean their system. This total cost includes a cost of labour of A$ 0.06 (the minimum wage in NTT is A$ 0.8/hour (Decree of the Governor of NTT, 2016). In addition, as the source of water can be a fair distance from the PV system, an extra cost about A$ 0.4 is needed for collecting water and other materials.

8. Results

8.1. Grid connected PV system in Perth

By deploying equations (1) to (5) supported with all data mentioned in section 7, the monthly energy produced by the 1.5 kWp system in Perth was obtained for each scenario (Fig. 6). To determine the total load capacity it was assumed that people are at work and the greatest loads are in the morning when the solar radiation is weak and in the evenings when the sun has already set. Data Analysis Australia (DAA), an organisation that provides services for survey and data analysis, analysed half-hourly electricity consumption data, collected as part of the Perth Solar City Program, for thousands of metropolitan residential customers in order to characterise the load profiles of different consumer groups (Data Analysis Australia, 2015). Based on the load profiles presented by the DAA, it can be estimated that the amount of energy consumption in daylight hours (6am to 6pm) is roughly 40% of the total daily energy consumption. Given the daily energy consumption values depicted in Fig. 5, the total load capacity over daylight hours can be calculated for each month and is contrasted with the energy produced by the PV system in those hours as presented in Fig. 6.

Fig. 6 shows that, due to its small capacity, the energy produced by the 1.5 kW system, in most cases, did not meet the electricity consumption of a 4-person household in Perth and surplus energy from the solar modules only existed during January. In addition, it can be seen that, starting in December, energy produced by the 1.5 kW system decreased progressively to the lowest point at the end of June, but then increased again and reached a peak at the end of the measurement period in November. The trend is in line with monthly solar irradiation data presented in Table 4.

Fig. 6 also shows that the presence of dust caused a decrease of energy generation under scenarios 2 and 3, compared to scenario 1. Applying equation 6, monthly energy losses were obtained as depicted in Fig. 7. Note that under scenario 1, the modules are cleaned every day, assumed to be in a constant clean condition and hence monthly energy losses are zero. Since the energy losses under scenario 2 were constant (5% per month), its monthly energy production will be 95% of the values in scenario 1. Scenario 3, however exhibited variation in losses; energy losses in February (the end of summer) and November (the end of spring) were greater than the other months. This indicates that the amount of dust attached on the PV cover glass over these two months was higher than the other months, as shown by the lower dust correction factors in Fig. 3. As mentioned in section 2, higher dust levels are attributed to lower rainfall occurring during the late spring/summer seasons as presented in Table 1. In addition, building renovation at the PV site at the end of spring also contributed to the greater energy losses. Calculation results reveal that totals of 109.58 kWh/year and 113.54 kWh/year of energy are lost by the system under scenario 2 and scenario 3, respectively.

Referring back to Fig. 6, the presence of dust increases the existing shortfall for all months apart from January. In January, the dust initially decreases the excess energy exported to the grid until there is no excess, and then reduces energy for self-consumption so that electricity must be imported from the grid. Based on these dust impact situations the cost of production losses *(C_{PL})* was determined by deploying equations 10 and 11. Taking into account the feed-in-tariff value in Perth is 7.13 cents/kWh (Energy Matters, 2017) and energy charge on flat rate tariff is 26.50 cents/kWh (Synergy, 2017) the annual C_{PL} of the system due to dust with degradation patterns of scenario 2 and scenario 3 is A\$ 28.44 and A\$ 29.50, respectively. This result reveals that the C_{PL} values are greater than the maintenance activity cost *(C_{MA})* value (A\$ 23 for one time cleaning of 10 PV modules) and indicates that it is economically viable for the PV system to undergo a cleaning procedure. Fig. 8 shows the C_{MA} and cumulative C_{PL} values and indicates that manual cleaning should be performed at the end of September for scenario 2 and in the middle of October for scenario 3 as marked with vertical dashed lines. After the cleaning, dust started to build up again on the surface of the PV modules and consequently it increased the C_{PL} although further cleaning was not required for the two scenarios. A different result was exhibited by scenario 1 where the PV modules are washed every day; the annual C_{PL} of the system was A\$ 0, while the C_{MA} was A\$ 8,395. The cost of cleaning the modules is much higher compared to the production loss costs avoided (about A\$ 28.44 and A\$ 29.50 for scenarios 2 and 3 respectively) and suggests that the owner of the PV system could afford to reduce the frequency of cleaning.

In addition to the method explained previously, optimal cleaning can be recommended based on the value of power loss of the PV system in the month when $C_{PL}>C_{MA}$. The power loss is the difference between power produced by the PV system in clean condition (at the beginning of the study i.e. December) and dusty condition (after exposure to the elements for a certain period). Referring to the assumption in section 2 that the effect of dust per day is similar over a month then the generated power in a dusty month can be determined by multiplying the system's power output in clean condition by its monthly dust correction factor *(DCF)* from Fig. 3. From Fig. 8, it is known that power loss values in September for scenarios 2 and October for scenario 3 determined the cleaning schedule in Perth. Calculation results suggest that PV owners in Perth should then clean their PV systems when power losses reach 0.05 kW and 0.07 kW for scenarios

2 and 3 respectively. In practice the PV owners can calculate the monthly power losses by deploying the data of power provided by their inverter. It is important to note that the power values should be recorded during clear days to avoid the effect of variation in irradiation.

8.2. Off-grid PV system in NTT

Similar to the system in Perth, by utilizing the solar irradiation, temperature data and de-rating factors, the monthly energy produced by a 50 Wp SHS in NTT was determined for each scenario (Fig. 9). As stated in the explanation of Table 2, it was assumed that the users employed demand management for this system. Energy produced by the PV system over daylight hours was used to charge a battery and to run a mobile charger, a TV, and a radio. The lights operated during the night time were supplied by the battery. From Table 2, it can be calculated that the lights consumed 21 W of power and 7 Ah of current for 4 hours per day. Considering the specification of the solar charge controller (12 volt, 10 A, efficiency 5% (Table 3)), the time to recharge the battery is about 0.73 hours per day.

Fig. 9 shows that the system could handle the load without interruption and there was excess energy. However, the presence of dust reduced the energy generation of the system. Monthly energy losses due to dust were determined via equation 6 and are shown in Fig. 10. Calculations revealed that the system lost about 4.43 kWh/year and 7.11 kWh/year of energy for scenarios 2 and 3, respectively.

Fig. 9 also shows that dust only reduces the excess energy of the system commonly used by the PV owners to charge additional batteries and other appliances. In the past, before using SHS, the owners used to charge the appliances at neighbouring villagers who are connected to the grid. To determine C_{PL} of the system, it was assumed that: (1) decreasing the excess energy meant that some of the extra appliances required charging at neighbouring villagers, with the amount of energy needed was indicated by the energy losses of scenarios 2 and 3; (2) the cost of electricity for asked by the neighbour for charging the appliances was 15.12 cent/kWh, which is the electricity tariff for a small load capacity household (Decree of the Minister of Energy and Mineral Resources, 2016). The result of calculations reveals that the C_{PL} caused by dust on SHS in NTT was A$ 0.68 and A$ 1.10 for scenarios 2 and 3, respectively. The values are higher than the C_{MA} value, which is estimated to be about A$ 0.5 per one time cleaning of a 50 Wp module. From Fig. 11, it can be seen that a manual cleaning should be performed at the beginning of August for the two scenarios as indicated by vertical dashed lines. Since dust re-accumulated on PV surface after the cleaning, C_{PL} increased again as shown in the figure. The rate of increase of C_{PL} under scenario 3 was greater than scenario 2; as a result for scenario 3, a manual cleaning needs to be performed again in the end of October. Assuming the PV module was washed every day (scenario 1), the annual C_{PL} of the system was A$ 0, while the annual C_{MA} of the system was A$ 182.5. This scenario exhibits a much higher cleaning cost than the benefit received.

Similar to the discussion in section 8.1, optimal cleaning of PV systems in NTT can be suggested by referring to the power loss values in the months when $C_{PL}>C_{MA}$, i.e. August for scenario 2, and August and October for scenario 3. It is found that a manual cleaning procedure should be conducted when power loss of the system reaches 1.84 W under scenario 2, and 5.17 W and 6.70 W for the first and second time respectively under scenario 3. A PV operator in NTT can deploy a multimeter to measure power generated by the PV system in clean and dusty conditions. The power values should be recorded during clear days to avoid the effect of variation in irradiation.

9. Discussion

Results revealed that when dust impinged on the surface of the examined PV modules, their monthly P_{max} output decreased, on average, around 4.5% and 8% for the systems in Perth and NTT respectively. Analysis of the dust impact based on real degradation in the field, represented by scenario 3, revealed that a total of 113.54 kWh/year (about 300 Wh/day) and 7.11 kWh/year (about 19.5 Wh/day) of energy was lost by the PV systems in Perth and NTT, respectively. The energy losses caused economic losses of A$ 29.50 and A$ 1.10 for the systems in Perth and NTT, respectively. In terms of the costs involved for each kWh of energy lost due to soiling under scenario 3, the Perth system has the largest cost at 25.98 c/kWh compared to the NTT system at 15.47 c/kWh. In the case of the Perth system, the majority of the cost of production losses is due to energy losses increasing the existing shortfall (Equation 10) and hence the cost for each kWh lost is close to the cost of purchasing electricity, which was 26.5 c/kWh. For the NTT system, the only costs related to energy losses are if users go to neighbours to charge additional batteries and hence the cost for each kWh lost is close to the price of charging at a neighbour's house, which was assumed to be 15.12 kWh. By performing a manual cleaning, the most appropriate cleaning method for the systems (Mohamed and Hasan, 2012), as per the recommended schedule for real dust-affected energy degradation in the field, a PV owner in Perth and an owner in NTT can save about A$ 6.50 and A$ 0.10, respectively. The values are the difference between the total cost of production losses and the cost of maintenance activities.

The findings of this study suggest that the impact of cleaning is not economically significant. However, the accumulation of dust on a PV cover does cause a degradation of energy produced by the systems. The cumulative effect of these losses would be significant if it was a very large PV system, such as a solar farm. Further, even a small loss in output would be a serious problem for PV applications, like the small scale PV system in NTT. If a cleaning procedure is applied to the SHS in NTT, the extra power from the cleaned panel can be used to supply basic needs for the villagers. For example, the 19.5 Wh/day of energy calculated as the loss of the PV system in NTT due to dust, could be used to run a 5 watt light emitting diode (LED) lamp for about 4 hours. The light intensity of these LED lamps is equivalent to 300 lumen (Khan and Abas, 2011), the minimum requirement lighting for a reading activity (Corbyn et al., 2013). The electricity can also be utilized for charging phones and running low power entertainment appliances.

In addition to these life quality improvements, cleaning is also to prevent hot spot phenomena. In light rain or high humidity conditions, dust landing on a PV surface will be dissolved by water vapour and form a thin layer (Cuddihy, 1980). This layer can stick to the PV glass cover for a long time period; the layer may get trapped by biological species including moss and lichen and become hard to remove (Haeberlin and Graf, 1998). Lorenzo et al. (2014) reported that the layer can rise the temperature of the shaded cell by more than 20 degrees over the other cells in the same PV module, leading to some destructive effects that degrade PV module performance permanently.

The difference of the impact of dust on energy and economic losses simulated with the dust-affected degradation patterns of scenarios 2 and 3 for the grid-connected system in Perth is not much as indicated by their C_{PL} values plotted in Fig. 7 and 8. This means that the standard soiling losses of 5% is fairly accurate and can be applied for modelling dust on a PV system in Perth. However, it should be noted that the system needs one time of cleaning per year. A different result was shown by the system in NTT. When the dust-affected losses modelled the real degradation in the field (scenario 3), a SHS in NTT needs two times of cleaning activity, slightly higher compared to modelling standard 5% soiling losses result (scenario 2), which suggests once a year. Therefore, the standard dust de-rating factor should not be applied for a SHS in NTT as it underestimates the dust effect that reduces the reliability of the system. From the previous explanation, it is concluded that a higher dust de-rating factor should be applied in NTT than in Perth. As mentioned in section 2, the decrease in output was caused by the greater amount of dust attached to the PV surface in NTT, confirmed by higher P_{max} degradation in NTT (12-15%) than in Perth (4-6%). The greater concentration of dust in NTT was attributed to the longer dry season, the lower tilt angle of PV module, and higher relative humidity in the location. Furthermore, the C_{PL} of the two systems simulated with scenario 1 was, understandably, A$ 0, but about A$ 8,395 and A$ 182.5 was paid to perform manual cleaning every day for the systems in Perth and NTT, respectively. Scenario 1 is clearly not cost effective and daily cleaning would not be recommended for these small-scale systems.

The accumulation of dust over a one year period caused a decrease of P_{max} output by about 4-6%% for the system in Perth (moderate climate) and 12-15% for the systems in NTT (tropical climate). The literature suggests that PVs installed in areas with lower precipitation that the two regions studied here may account for greater performance degradation over an even shorter period. For example, a study carried out in Dhahran (desert climate) reported that there was a P_{max} output loss of more than 50% experienced by PV modules exposed for about 6 months (Adinoyi and Said, 2013). The loss, of course, leads to greater energy and economic losses. Therefore, in addition to sizing with a higher de-rating factor, more intensive dust prevention and performance restoration activities are needed for PV system in low precipitation areas.

It is important to note that the daily load capacity data in Perth used in this research was a simplification based on a typical group of consumers in Perth. Further studies can be done to improve the modelling of energy and economic losses caused by dust by investigating different percentages of electricity consumption during daylight hours for a household, different system sizes and varying costs and tariffs.

The study is limited to the effect of dust on the performance of PV modules at the end of each season over a one year period in 2015. Since monthly performance degradation due to dust would vary from year to year, the C_{PL} data provided in this paper could not be used for modelling the optimal cleaning schedule for several years of PV system operation in Perth and NTT. Further research is needed with more frequent measurement and longer time periods to obtain a clear figure of PV degradation dictated by dust and environmental conditions.

10. Conclusion

This research investigated the energy and economic losses caused by dust on residential PV systems deployed in Perth, Australia, a temperate climate region, and Nusa Tenggara Timur (NTT), Indonesia, a tropical climate area. Energy losses of a 1.5 kWp grid connected PV system in Perth and a 50 Wp solar home system (SHS) in NTT due to dust, with a degradation pattern as measured in the field at the end of every season, was 113.54 kWh/year (about 300 Wh/day) and 7.11 kWh/year (about 19.5 Wh/day) respectively. Economic modelling showed that, the cost of production per kWh lost due to dust exhibited by these systems were A$ 0.26/kWh and A$ 0.15/kWh, respectively. The cost per kWh lost is a useful metric with which to compare different systems and is influenced by the local situation in terms of excess or shortfall between PV output and load, the possibility of selling excess power and the costs of making up the shortfall. The optimal time to perform a manual cleaning procedure was in the middle of October (P_{max} loss by 0.07 kW) for the system in Perth, while at the beginning of August (P_{max} loss by 5.17 W) and in the end of October (P_{max} loss by 6.70 W) for the system in NTT. By doing a cleaning activity as per the suggested time in the real dust degradation scenario, a PV owner in Perth and NTT can save about A$ 6.50/year and A$ 0.10/year, respectively. Although the cost of production losses is not economically significant for these small-scale systems, cleaning PV modules is recommended as it prevents hot spot phenomenon leading to a permanent performance degradation. Further, the excess energy from the module improves the renewable energy fraction from the system and, particularly in NTT, improves the quality of life. The insignificant economic impact of cleaning, however, signals that dust mitigation procedures on small scale PV systems, including surface technology modification such as coating, may not be appropriate as it, will increase system costs over and above whatever savings could be gained in performance. The standard dust de-rating factor (5%) is appropriate for modelling a grid-connected PV system in Perth, but, the system requires cleaning once per year. Conversely, the standard soiling loss factor of 5% is not suitable for SHS modelling in NTT as the estimation of the impact of dust is underestimated. Therefore, higher dust de-rating factors and more cleaning activity may be more appropriate for PV systems deployed in tropical climate areas compared to that in temperate climate regions. Further, comparing the two regions, much higher de-rating factors and more intensive prevention and performance restoration procedures should be applied for systems installed in regions of the world with low precipitation such as deserts. It is recommended that PV system Standards that use the 5% performance de-rating factor due to soiling, such as AS4509.2 (Australian/New Zealand Standard, 2010), are reviewed and consideration given to climate-dependent de-rating factors.

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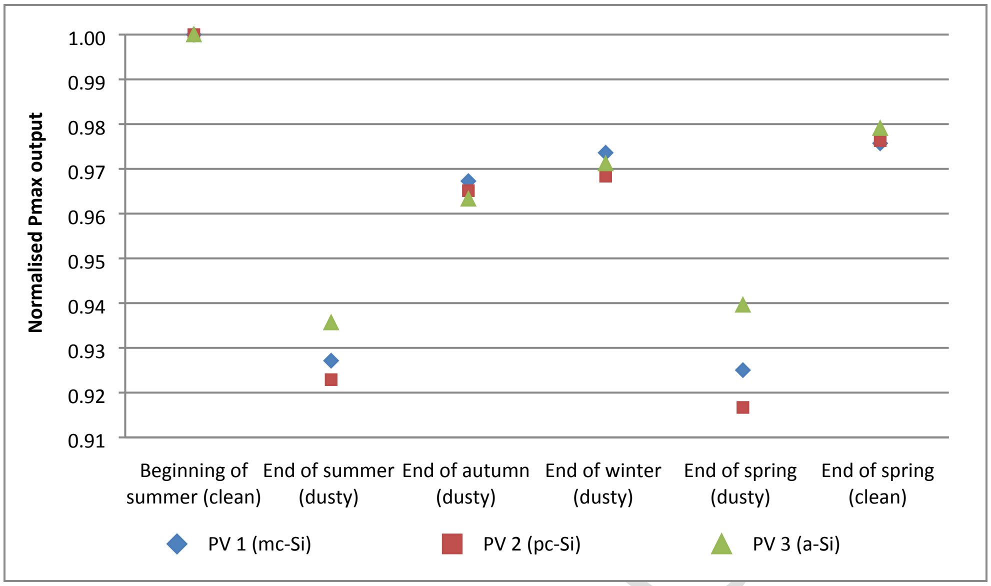

Fig. 1. PV modules' performance every season at ROTA.

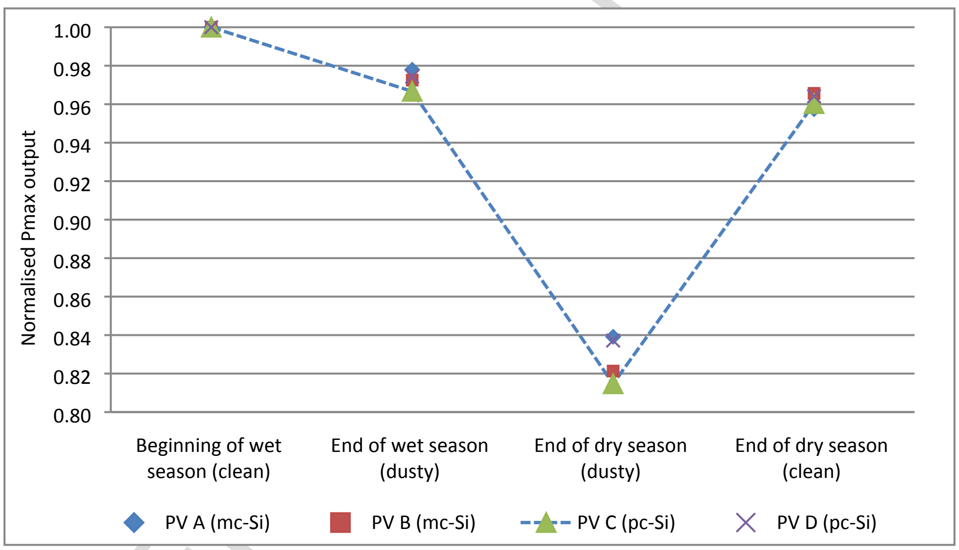

Fig. 2. PV modules' performance every season at PNK.

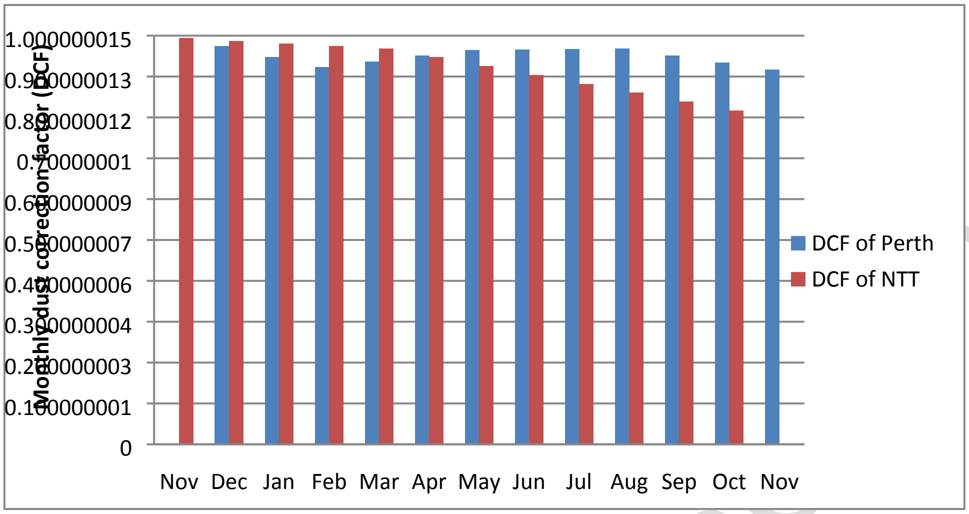

Fig. 3. Monthly dust correction factor *(DCF)* of Perth and NTT

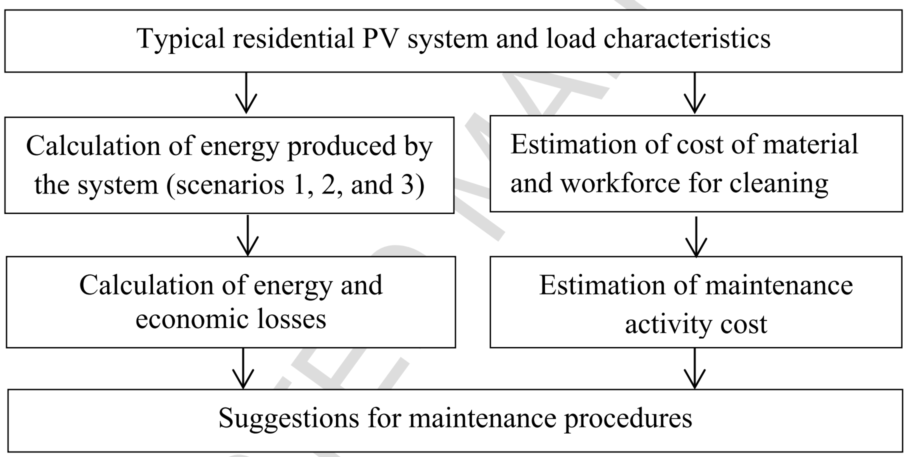

Fig. 4. Methodology to determine energy and economic losses caused by dust.

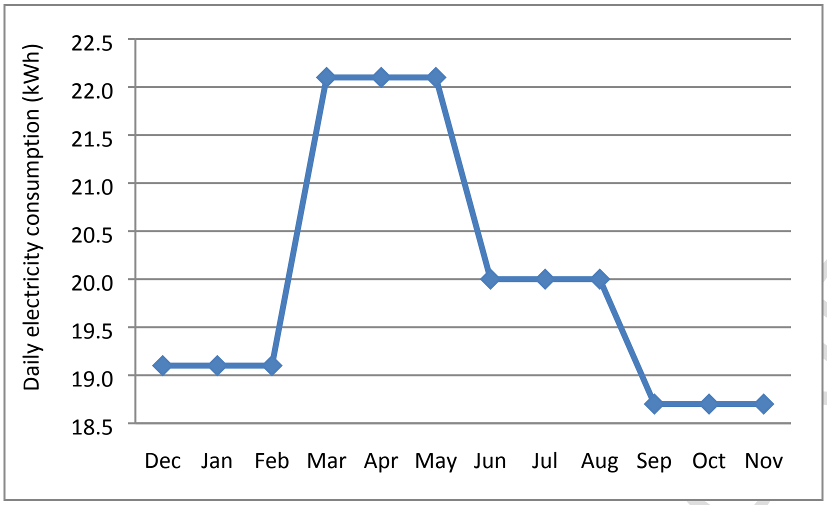

Fig. 5. Typical daily electricity consumption of a 4-person household in Perth.

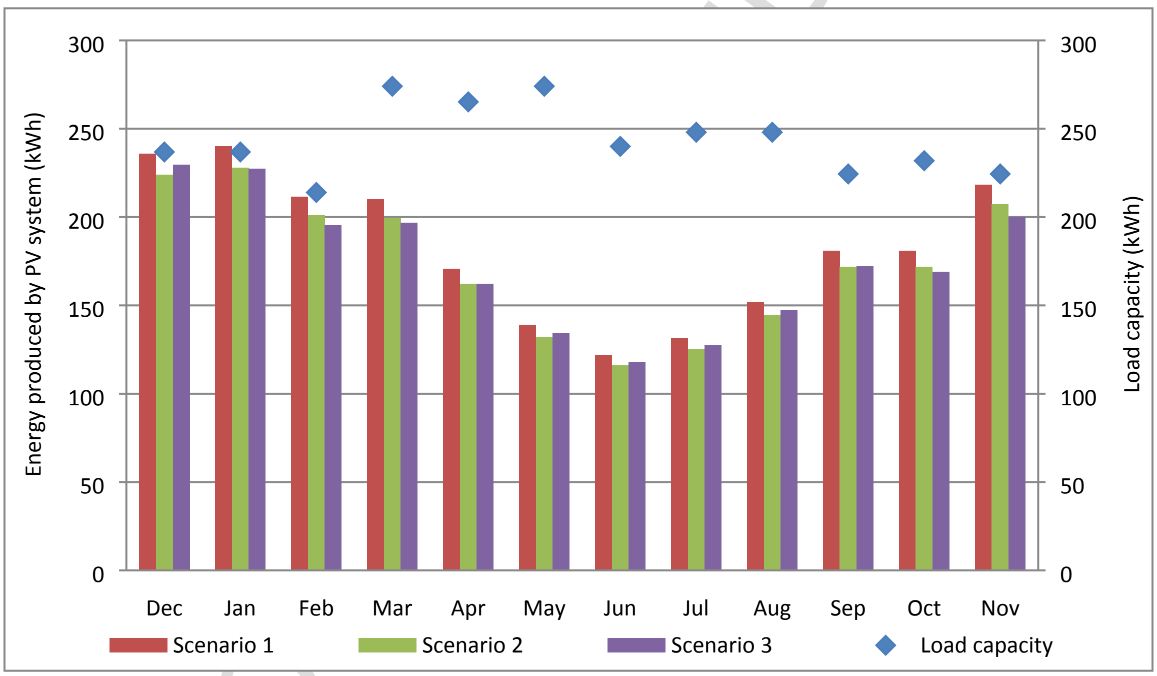

Fig. 6. Energy produced by a 1.5 kWp system in Perth.

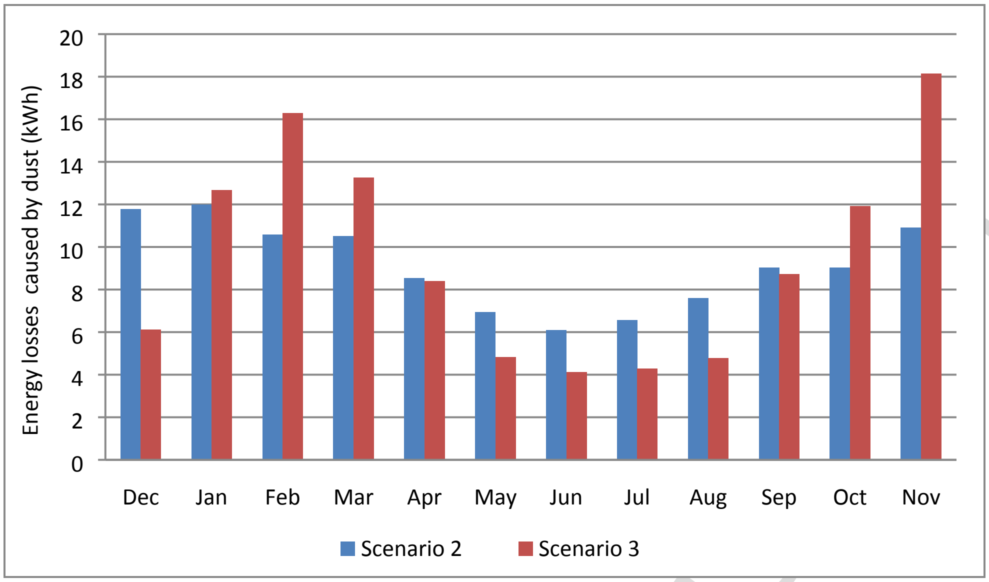

Fig. 7. Energy losses caused by dust on a 1.5 kWp system in Perth.

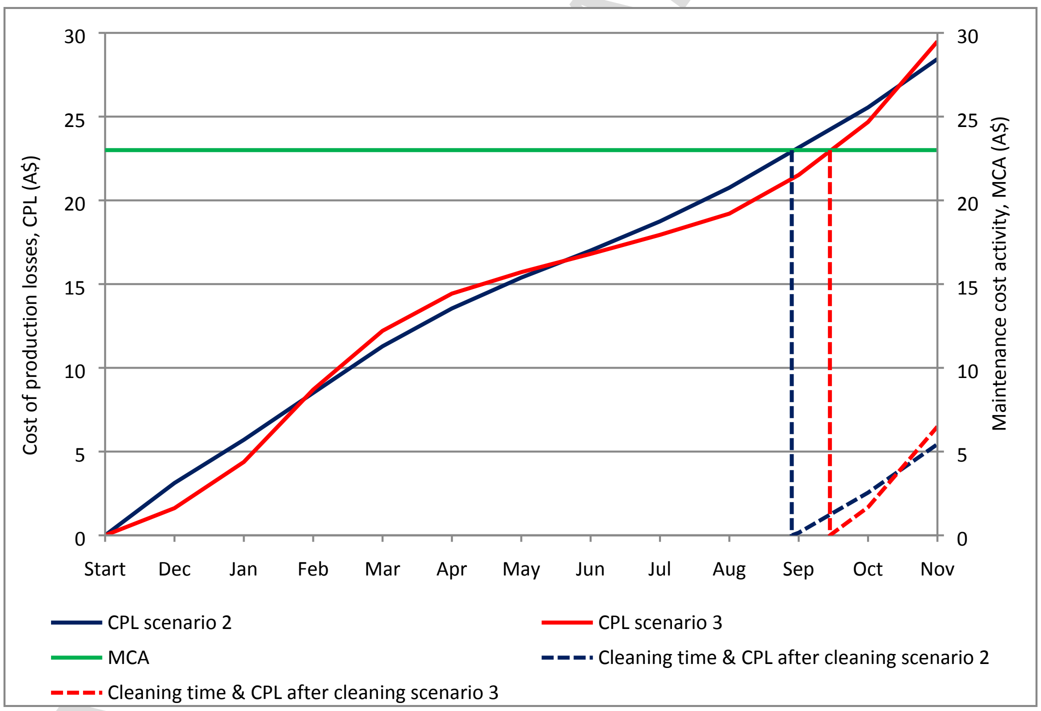

Fig. 8. C_{PL} and M_{CA} of a 1.5 kWp system in Perth.

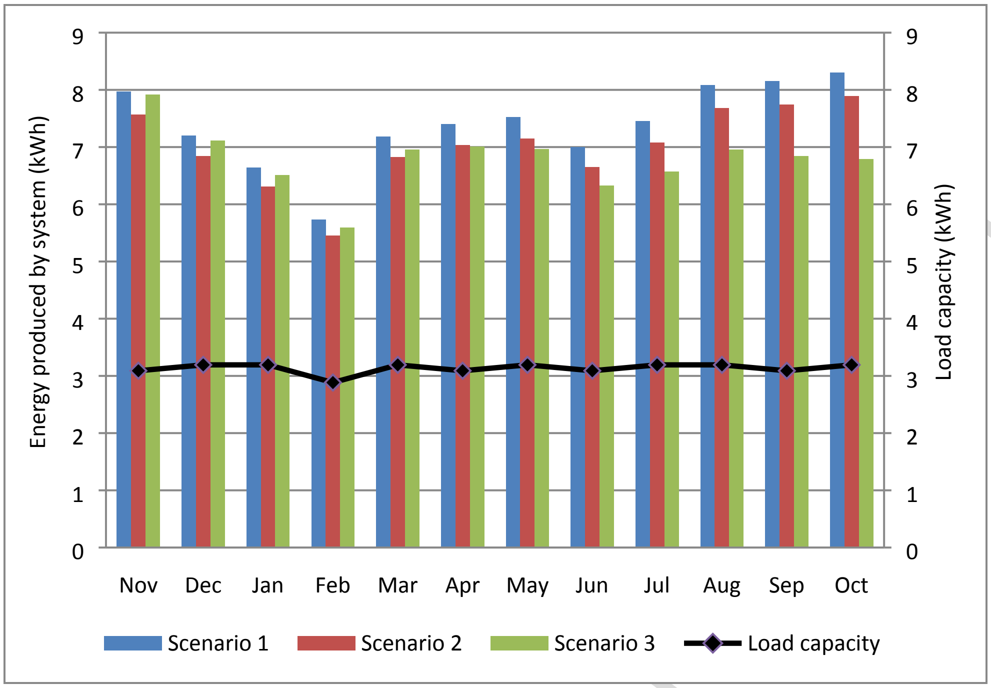

Fig. 9. Energy produced by a 50 Wp SHS in NTT.

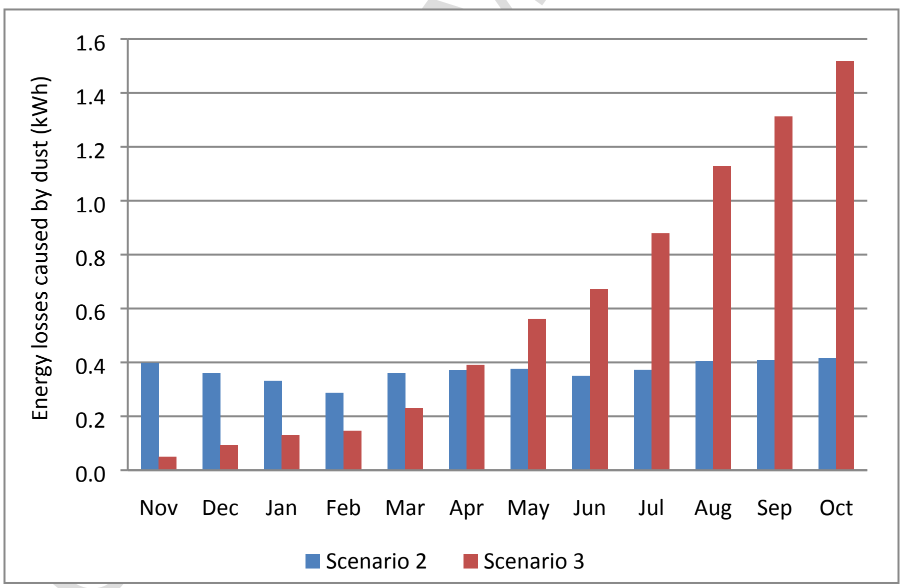

Fig. 10. Energy losses caused by dust on a 50 Wp SHS in NTT.

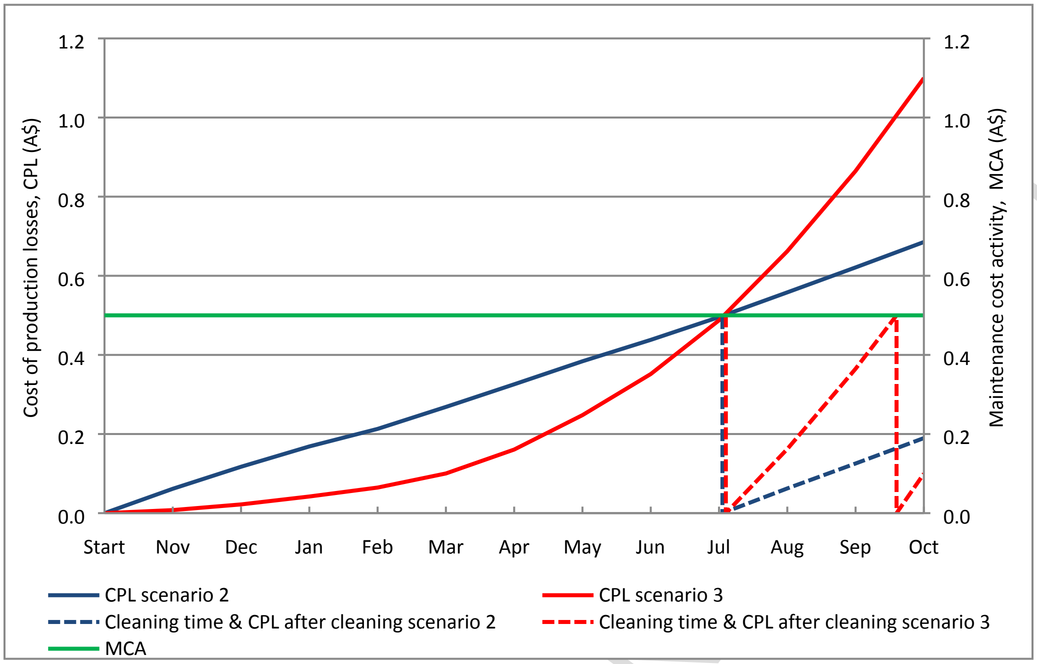

Fig. 11. C_{PL} and M_{CA} of a 50 Wp SHS in NTT.

Highlights:

- Energy losses of a 1.5 kWp grid connected PV system in Perth, Australia and a 50 Wp solar home system in Nusa Tenggara Timur (NTT), Indonesia due to dust, with a degradation pattern as measured in the field at the end of every season, were 113.54 kWh/year and 7.11 kWh/year, respectively.
- The optimal time to perform a manual cleaning procedure was in October for the system in Perth, while in August and October for the system in NTT.
- A higher dust de-rating factor and increased cleaning activity required for PV systems deployed in tropical climate areas compared to those in temperate climate regions.

Table 1. Monthly climatic condition of ROTA and PNK over the period of study (Murdoch University Weather Station, 2016; Bureau of Meteorology, Climatological and Geophysics of Kupang, 2015)

Month	Average temperature (°C)		Maximum temperature (°C)		Accumulated rainfall (mm)		Rainy days		Average wind speed (m/s)		Average relative humidity (%)	
	ROTA	PNK	ROTA	PNK	ROTA	PNK	ROTA	PNK	ROTA	PNK	ROTA	PNK
Nov ‘14	19	28.6	38.32	33.5	13	20	7	4	2.27	2.39	60.91	78
Dec '14	21.27	29	44.98	32	1	201	1	14	2.39	2.44	51.82	82
Jan '15	24.58	27.9	38.99	30.8	2.5	659	1	23	2.42	2.29	44.96	84
Feb '15	24.36	27.3	35.76	31.2	23.2	112	3	17	2.29	2.29	57.29	85
Mar '15	22.15	27.2	29.89	31.4	16	339	5	16	2.29	2.38	55.46	87
Apr '15	19.1	28.1	26.07	33.3	44	61	8	4	2.38	2.02	58.07	79
May '15	14.77	27.3	25.33	32.9	72.5	13	6	2	2.02	2.15	67.24	74
Jun '15	14.83	26.8	22.63	32.5	62.5	0	9	-	2.15	1.96	73.42	71
Jul '15	13.45	26.2	27.72	31.9	117.5	4	17	1	1.96	2.12	78.75	70
Aug '15	14.01	26.1	32.06	32.1	70	0	13	-	2.12	2.21	74.11	67
Sep '15	15.39	26.7	33.74	32.3	33.8	0	6	-	2.21	2.08	62.13	69
Oct '15	18.97	27.8	39.6	32.6	47	0	6	-	2.08	2.28	65.09	63
Nov '15	20.84	29.5	38.32	33.3	16.7	17	6	3	2.28	2.39	58.98	76

Table 2. Assumed load characteristic of PV system in NTT.

Description	Base case load	Hours of use per day	Days of use per week
	W	h/d	d/w
Lights (2 x 8 watt)	16	4	7
Light (1 x 5 watt)	5	4	7
Radio/cassette player	6	1	7
Mobile charger	3	1	7
TV	15	1	7

Table 3. De-rating factors of PV system in Perth and NTT.

Variable	Grid-connected PV in Perth	SHS in NTT
f_{man} (%)	3	3
Υ (%/°C)	-4.5	-4.5
T_{STC} (°C)	25	25
T_r (°C)	35	20
η_{inv} (%)	96	-
η_{pv_inv} (%)	3	-
η_{inv_sb} (%)	1	-
η_{coul} (%)	-	95
η_{charge} (%)	-	95
f_{cable} (%)	-	3

Table 4. Monthly solar irradiation and temperature of Perth and NTT (NASA, 2016).

Month	Solar irradiation (kWh/m^2)		Average temperature (^oC)	
	Perth	NTT	Perth	NTT
Jan	7.46	5.83	25.5	26.6
Feb	7.28	5.57	25.4	26.4
Mar	6.53	6.30	23.1	26.4
Apr	5.48	6.72	19.4	26.8
May	4.32	6.61	15	27
Jun	3.92	6.33	12	26.4
Jul	4.09	6.50	10.8	26.1
Aug	4.72	7.05	11.2	26.3
Sep	5.81	7.38	13.3	27.2
Oct	5.62	7.31	16.3	27.7
Nov	7.01	7.20	20	27.4
Dec	7.33	6.33	22.9	26.8
Annual	5.87	6.6	17.9	26.8